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Automated In -Situ Inspection Systems for Underground Storage Tanks

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The Army has 20,000 underground fuel storage tanks (USTs) that must be brought into compliance with the new federal regulations by 1998. To be compliant a tank must be closed, upgraded or replaced. This report covers the investigative research for the development of a robotic system capable of performing an in situ ultrasonic thickness inspection on the interior of a fueled UST. The robotic system is designed to meet the criteria outlined in the Draft Standard for the Robotic Inspection of Underground Storage Tanks developed for the EPA. This robotic inspection will allow the Army to make an informed decision on the appropriate action to be taken for a given tank. The robotic system offers a cost effective way to monitor a tank when compared with the existing manual technology that produces the same results. The robotic technology also moves the human out of the UST which eliminates the human liability factor in the hazardous environment.

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FOREWORD

This research was performed for the US Army Construction Engineering Research Laboratory (USACERL) under contract number DACA88-93-C-0008. This contract was issued as a Phase 1 project in conjunction with the Small Business Innovative Research (SBIR) program Topic: A92-143 Titled: Automated In-Situ Inspection Systems for Underground Fuel Storage Tanks. Mr. Vincent F. Hoch is the technical Point of Contact for this project.

The research was conducted by RedZone Robotics, Inc. of Pittsburgh, PA. Christopher C. Fromme was the Principal Investigator and Warren C. Whittaker was the Lead Engineer for the project.

DR. L.R. Shaffer is the Director of USACERL, Lt. Col. David Rehbein is the Commander of USACERL and Dr. Paul Howdyshell is the Division Chief.

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CHAPTER 1. INTRODUCTION

Background

Federal and Army regulations require that all underground fuel storage tanks (USTs) be in compliance with the most stringent policy governing leak detection, corrosion protection and spill/overflow prevention. All tanks must be in compliance by 1998 to continue operations. The magnitude of these requirements can only be understood when one realizes that there are an estimated 2 million USTs in use in the United States, with the Army alone operating over 20,000. The majority of these tanks are old designs and installations that may require significant retrofit to come into compliance. The driving force behind these regulations is the recent attention given to leaking USTs that have caused soil and ground water contamination and, in a few cases, fatal explosions. Given the large number of older USTs in service, without proper inspection procedures, these events will become more frequent. It is estimated that to bring the tanks into compliance will cost $20,000 each; the cost to clean up contaminated soil or ground water is many times the cost of inspecting, repairing or decommissioning the tanks.

The problem facing the tank owners is how to make an informed decision about what actions to take regarding a specific tank. Most of the current technologies only tell the owner if his tank is leaking or not leaking and do not analyze the condition of the tank. The best technology available to make an accurate analysis of the tank's condition requires entry to conduct tests. Entry into the tank requires an extensive operation to drain and purge the tank before humans with breathing apparatus can enter. The best data for analyzing a tank comes from conducting an ultrasonic transducer (UT) thickness survey.

The ultimate goal of the Army program is to analyze their USTs in-situ and manage these tanks. USACERL is developing several techniques to statistically analyze the condition of a UST by integrating several pieces of data. The one key element in this program is to obtain the UT thickness survey of the tank.

Objectives

This report covers the research for the development of a robotic system capable of performing an in-situ automated ultrasonic thickness inspection on the interior of a fueled UST. The concentration of this study has been to identify the specifications for and the identification of the component technologies required for the integration of the robotic system. The key systems investigated were the robot mechanism, the positioning and sensing devices, the UT inspection hardware, the operator station hardware and the system software. Due to the hazardous UST environment, hazardous certification was also researched because of the impact on the design.

Abstract

Chapter 2: We evaluated different options for the mechanism used to deploy the sensing equipment in the tank and defined the robot performance specifications. This task was accomplished by surveying various UST configurations and looking at commercial robotic systems that performed elements of this work. Our engineering department held brainstorming sessions to define the specifications.

Chapter 3: We defined the functional specifications of the UT inspection system, and identified the sensing equipment capable of meeting those requirements. We accomplished this task by reviewing agency standards and investigating the UT equipment manufacturers and inspection companies.

Chapter 4: We defined a specification and strategy to integrate hardware and software in order to know the position of the robot in the tank. This was accomplished with a literature search and by drawing on our accumulated engineering knowledge on this subject.

Chapter 5: We defined the design consideration for hazardous area certification and the certification process. We first researched the regulations that govern operation in a hazardous environment. This research led to the conclusion that elements of the robotic system hardware needed to be designed for operation in this environment. Research into the design considerations led to the need for certification of the hardware for operation in these environments and the research of the certification process.

Chapter 6: W integrated the elements from the previous chapters into a robotic UST inspection system. We accomplished the design of the system by drawing on the expertise of RedZone engineers and the expertise of component manufacturers.

Chapter 7: We fabricated a UST mockup and a mechanical device to investigate the mobility issues and dead reckoning capabilities of our chosen design. Based on the tests performed we refined the robotic design.

Chapter 8: We drew conclusions and made recommendations for the system design.

Limitations of Scope

We limited the study focus to steel tanks to take advantage of magnetics in the robotic design. Steel tanks represent the majority of the underground storage tanks that are to be investigated. Much of the research conducted and presented in this paper is transferable to robotic systems that would be used for non-ferrous underground storage tanks.

The robot design was limited to deployment into a UST through a 4 inch pipe. Scalability of the robot concept is discussed in Chapter 6 of this paper.

This study focused on the robotic issues and the EPA requirements for collecting the raw UT data. However, this study did not focus on the post-processing of the raw UT data for integration into a tank assessment. The statistical analysis of the raw UT thickness data will be handled by USACERL.

The robot mockup constructed during this research was developed specifically to study mobility and dead reckoning concerns. This system is described in Chapter 7.

Mode of Technology Transfer

RedZone is supplying this document as the technology transfer for the fulfillment of the phase 1 work of this SBIR program.

In the phase 2 work of the SBIR program RedZone Robotics, Inc. intends to develop a prototype robotic system that will be designed for use in the hazardous UST environment. We will also patent the system. The technology transfer will be a demonstration of the robotic system in RedZone's UST mockup and the documentation developed with the program.

Under phase 3 of the SBIR program RedZone will commercialize the robotic system. The robotic system will be made available to service contractors who will offer complete UST inspection services to the Army thus completing the technology transfer.

CHAPTER 2. DESIGN SPECIFICATIONS

UST Specifications

The following list is a summary of the typical UST parameters:

- Cylindrical in shape with flat end caps.
- Steel or fiberglass construction.
- Wall thicknesses for steel tanks are 1/8 in. (3.2 mm) to 3/8 in. (9,5 mm).
- Tank volumes are 500 gallons (1.89 kl) to 50,000 gallons (189 kl).
- Diameters of the tanks are 4 ft (1.21 m) to 12 ft (3.66 m).
- The lengths of tanks are 5 ft (1.52 m) to 60 ft (18.3 m).
- Most USTs have at least one 4 in. (101.6 mm) access riser. Some of the small, older tanks only have 2 in. (50.8 mm) and 3 in. (76.2 mm) risers.

Draft Standard Specifications

The following selected specifications affecting the robot system design come directly from the Draft Standard For The Robotic Inspection of Underground Storage Tanks submitted to the Environmental Protection Agency. This standard, once approved, is to govern the use of the robotic systems researched in this contract:

A5.1.4 STATIC ELECTRICITY CONTROL: Adequate precautions shall be taken to prevent the accumulation and discharge of static electricity (See NFPA 77 Recommended practice on Static Electricity)

A5.1.5 ELECTRICAL EQUIPMENT: During site preparation, all electrical equipment used in the vapor area shall be safe for operation in the defined environment. Ground fault interrupts are required for portable electric equipment.

A6.2.2 SURFACE PREPARATION: In accordance with ASTM E 114, all surfaces to be examined shall be uniform and free of loose scale and paint, dirt or other deposits which affect examination results to the extent possible. The surface must be adequate to permit ultrasonic examination at the sensitivity specified. The surfaces may be prepared for examination purposes, in a manner compatible with the stored product environment, by the robotic inspection apparatus.

A6.2.5 COUPLANT: The couplant shall be the stored product or a material compatible with the stored product and shall be appropriate for the surface finish of the material to be examined. The surface finish and couplant of the reference standards shall be acoustically similar to those of the tank.

A6.2.6 ULTRASONIC GAUGING:

A6.2.6.1 The ultrasonic equipment used in the robotic inspection of underground storage tanks shall take lateral measurements every 4-6 inches of linear feet of travel throughout the

entire interior surface of the tank at a maximum axial spacing of 3 feet. Where corrosion damage is more severe the distance shall be not more than a distance less than 3 feet determined by the inspection engineer to provide adequate inspection data.

A6.2.6.2 Depending on entry surface conditions, the minimum UT thickness measurement capability may vary from 0.050 - 0.125 inches. The instrument should be able to measure remaining wall thickness to an accuracy of ±0.010 inches and to detect a flat bottom hole of 0.125 inches diameter.

A6.2.6.3 The system should demonstrate position accuracy and repeatability which supports statistically meaningful determination of wall condition.

A6.2.7 ROBOTIC SPECIFICATIONS

A6.2.7.1 The robotic inspection device shall be able to enter the tank through a minimum 4 inch opening and shall be versatile enough to enable it to traverse 100% of the interior of the tank.

A6.2.7.2 ASTM E 114requires that for automated scanning, the search unit be held by a suitable fixed device

A6.2.7.3 The robotic crawler shall be able to free the interior surfaces of the tank from rust, loose scale, paint and other deposits as required by A6.2.2 above, to ensure a clean surface for ultrasonic inspection.

A6.2.7.5 .... The robotic inspection system shall be safe for operation in the defined environment.

Robotic System Specifications

RedZone developed these additional specifications for the robotic system design:

- The tank must be constructed of steel.
- The tank can contain any level of fuel.
- The robot must be capable of traversing 100% of the interior tank wall, including the end caps.
- The system will be capable of operating in underground fuel storage tanks without defueling.
- The positioning system will be capable of an accuracy to at least 5% of the traveled distance.
- The robot will be capable of deploying a 5 lb. payload package.
- The payload can be delivered up to 100 ft from the surface entry point.
- The robot must be capable of inspecting a clean tank at a rate of 250 sq ft per hour. The tank cleaning and sludge removal tasks needed for inspection may take substantially more time.

Robotic Approaches

We identified several approaches for a mechanism to deploy the sensing capability:

- Swimmers, based on remote ocean vehicles, can be used to deploy sensors in full tanks. However, swimmers lack the required positional stability for effective ultrasonic imaging,

and require that the tank be full for 100% inspection. They do not lend themselves to automated scanning due to lack of precise incremental motions.

- Long reach manipulators, as used to inspect nuclear reactor vessels, could be applied to USTs. There are a number of significant disadvantages to this approach including the large size of the equipment required to reach the entire interior, small cross sections needed to access tanks and the instability of the endpoint in a long reach configuration.

- Wall-walkers are mechanisms that attach to walls via suction or magnetism and walk around with simple gaits. The disadvantages of these devices are the length of time required to make an excursion from one end of the tank to the other and the possibility of problems attaching through heavy sludge or debris. The two means of achieving wall attachment are discussed below:

Magnetics - either electromagnetic or permanent magnets with a degaussing procedure can be used. Magnetics are limited because they only work on metallic tanks; however, the older tanks are predominantly metal.

Suction - can be applied as active or passive. Active would require that a vacuum be pulled under the attachment pad. Passive simply uses pressure to remove air from under the pad. Suction devices work on plastic as well as metal tanks.

- Magnetic-wheeled or tracked crawlers are devices that use magnetics to generate enough attraction with the wall to allow the wheels or tracks to move the device. The advantage is they are fast and are coupled with the wall surface to be inspected. Difficulties are primarily related to slippage in turning and transitioning to the walls.

Our research into existing systems and brainstorming efforts led to the selection of a magnetic-wheeled system as the best deployment platform because:

- They maintain good positional accuracy.

- They are simpler mechanisms, hence easier to control than the others

- Their weight and profiles do not increase with the size of the inspection region, as with manipulators.

- There is a precedent for the deployment of wheeled vehicles for robotic UT inspections on tanks.

We discussed the following configurations:

- Skid steered vehicles drive by having all of the wheels or tracks on each side of the vehicle grouped together. Driving occurs when both sides are driven together in the same direction at the same speed. Turning occurs when one side is driven at a different speed from the other. The turning occurs by skidding the wheels along the surface. Depending on the interaction with the tank surface and the attractive force of the magnetics, this skid steering may not be predictable on the tank surfaces.

- Ackerman steered vehicles and tricycles operate by having one or two steering wheels and the steering or the rear wheels also drive. This system is like an automobile and requires extensive planning to execute turns and back out of a situation. This system also requires integrating the steer and drive motions to calculate position.

- Articulated vehicles operate by pivoting the center of the vehicle. These systems have a limited turn angle and because of the pivot in the center the mechanics become complex. These vehicles, like the Ackerman scenario, require extensive planning for conducting turns.

- All steer all drive vehicles work by steering all of the wheels and driving with all of the wheels. The advantage to this type of system is that you can travel in any direction anytime without changing the orientation of the vehicle. The swept volumes to steer the wheels made this design to large for a 4 in. access.

- Center pivot vehicles drive by having one motor to drive all of the wheels or tracks in the same direction. This drive offers the best tractive forces for straight driving just like the skid steer vehicle. This vehicle turns by stopping, standing on a central pivot foot which raises the wheels off the surface, pivoting and raising the foot, and placing the wheels back down on the surface in the new orientation. This system has the advantages of excellent traction, excellent dead reckoning and simple motion control.

We choose the center pivot vehicle as the best configuration.

CHAPTER 3 UT SENSING HARDWARE

The goal of this system is to build a tank wall thickness map, based on UT sensor readings throughout the tank. The functional specifications for the inspection system, were defined in the Draft Standard For The Robotic Inspection of Underground Storage Tanks submitted to the Environmental Protection Agency.

During this task we contacted manufacturers, inspection companies and researchers to identify the UT technologies capable of meeting the inspection criteria and available for integration onto a robotic system. The following is a summary.

- All of the UT technologies identified require cleaning and good contact with the steel surface.
- All of the UT equipment manufacturers have standard equipment capable of taking the thickness data as confirmed by the inspection companies currently conducting these tests manually.
- Of the companies contacted only A.M. Data of Windsor, CT stated that they had collected UT data in a hazardous environment. Most of the manufacturers stated they are interested in supporting the development of an UT sensor for the hazardous environment.
- Multiplexing many UT sensors can provide higher density scans or broader area coverage with each pass. Looking at the draft standard criteria the sensing can be accomplished by using one UT sensor thus avoiding the additional costs.
- The emerging technologies, including Innovative Dynamics' UT sensor system, are not ready for integration at this time.
- We have allotted space and payload capacity in the design to implement future developments in the UT sensors or to allow for equipment integration to carry out more stringent UT inspections.

RedZone is currently involved with the integration of a UT sensing system on a robot for inspecting the double wall inspection tanks at the Hanford, WA Department of Energy site. This work is being conducted for Ebasco Services, Inc. of New York, NY a leader in tank inspection service. The development model laid out for the Hanford project is viewed by RedZone as the best way to ensure successful UT inspection and robot integration. The model of development follows:

- Select an inspection company who is actively pursuing the UST inspection market.
- Have the inspection company work with the UT equipment manufacturers to select the appropriate sensing head and recording equipment needed to conduct the survey.
- RedZone will work with the UT equipment manufacturer to integrate the sensing device into the robotic system in order to assure successful hazardous location certification.
- RedZone will develop the couplant supply mechanism. The inspection company will specify the couplant to be used with the different tank products to assure proper inspection with the UT head.
- RedZone will develop the cleaning mechanism. The inspection company will define any limitations in surface conditions that can be inspected and the capabilities of the cleaning system.

- RedZone and the inspection company will conduct testing to guarantee the success of the system.

By following this model and integrating the inspection company from the outset we can assure the success of the UT inspection and the future acceptance and availability of the inspection service.

The following are the design elements required for the development of a UT inspection system for the hazardous environment. The discussions of each element include our research:

Transducer

The transducer is the actual sensing device used to take the readings of the thickness of the metal and can be purchased from most UT equipment manufacturers. The manufacturers contacted all have transducers that meet the requirements of the draft standard requirements. Commercial thickness transducers require a high voltage trigger pulse for operation. The high voltage prevents the sensor from being classified as intrinsically safe. Therefore the unit must be classified as explosion-proof or purged and pressurized. A custom transducer that is sealed and the input wiring purged and pressurized should be capable of being certified for operation in the hazardous environment.

Couplant

Couplant is required by the transducer to fill the voids between the transducer head and the tank surface being inspected to assure accurate readings. We will either use the product as the couplant or we will have to supply a material compatible with the product as the couplant.

The difficulty in using the product as the couplant is keeping the contaminants produced during cleaning from fouling the sensor head and pumping the volatile liquid into the vapor space above the fluid level in the tank. The product can be actively filtered for use when submerged in the tank requiring an on-board filter system. The more difficult problem is certification of the pumping system and the danger of volatizing the head space above the fluid level.

Using a couplant compatible with the product requires a reservoir on board the robot or a supply line beside the tether. The impact of the compatible couplant on the product will need to be analyzed. Installing a couplant recovery system that re-uses the couplant will minimize the volume required for the inspection.

The couplant strategy used will depend on the product in the tank and the volume of couplant required by the inspection head. The mechanical deployment devices for either couplant method can be adapted to the robot.

Cleaning

Prior to taking a thickness reading, a spot on the tank must be cleaned. In order to minimize the contamination of the product, we are proposing that the robot clean areas slightly larger than the probe for inspection. The cleaning will occur automatically while the robot is driven. As the robot moves ahead a cleaning brush will clean the surface of the tank and the contaminants will be vectored away from the inspection head by a guard.

Inspection Head Deployment

In order to inspect the tank wall successfully, the sensing head must be in contact with the surface of the wall. To accomplish this a mechanical spring-loaded device will keep a small sled in flat contact with the wall. The sled will contain the sensing head and a couplant supply line. The head will incorporate contact switches to assure alignment and contact force.

Data Collection

A commercial UT thickness data management system will be used to collect and report the raw data for the tank. RedZone will integrate the positional data from our robot controller to the commercial UT equipment.

CHAPTER 4. POSITION SENSING

Several approaches to the positioning problem including acoustic sensors, dead reckoning, vision, geometric and tactile based schemes were investigated.

Acoustic Sensors

Acoustical sensors, such as sonar, are impractical for general positioning of the robotic system in the tank. They are subject to problems generated by the echoes in the tank and are also subject to the acoustical properties of the product in the tank. The data returned is significantly different when there is fluid present fror . when the tanks are empty. Acoustical sensing can be effectively applied for close proximity sensing applications.

Dead Reckoning

Dead reckoning relies on the accuracy with which small motions can be measured. Using an encoder for feedback on the drive motor of the robot, we can determine the distance traveled or angle turned. Once a reference frame to the tank has been established, accurate position can be determined by tracking the robot's motions. Error will be introduced into this measurement by slippage between the robot and the tank. Accuracies of better than 1% of distance traveled are typical with dead reckoning systems.

Geometric

Geometric sensing uses gravity and trigonometry to provide simple accurate position within a tank. The angle of the sensor with respect to gravity can give the height along a cylindrical tank wall. The angle of the inspection system from the access port can give other measurements needed to determine the exact position.

Vision Systems

Vision systems are extremely limited by the inability to see through the product when submerged. However, we feel that a camera could be used to view the tank surface through a thin layer of product. The ability to identify plate seams in the tank could be used as a supplemental positional reference. The problem with these vision systems is the robot operator must either interact to tell the positioning system of the event or the vision system must be automated which requires expensive hardware and software.

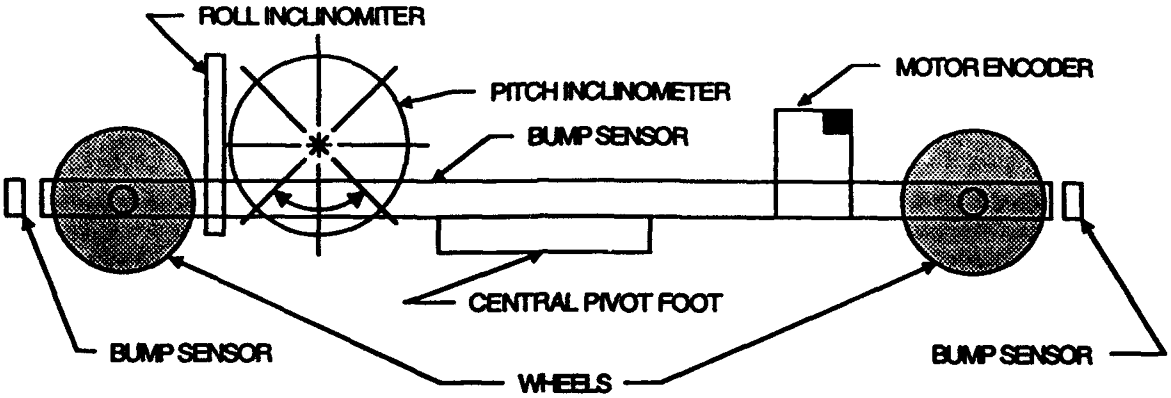
Tactile Systems

Tactile systems include bump sensors and proximity sensors. These systems tell you where an obstacle or end cap is located by contacting or nearly contacting the surface.

Positioning Scheme

Using these technologies we developed the following scheme to establish and monitor the position of the robot within the tank. This scenario addresses the scheme for operation in a horizontal cylindrical tank. Refer to Figure 1 Robot Sensor Layout for the sensor layout on the robot.

SIDE VIEW



TOP VIEW

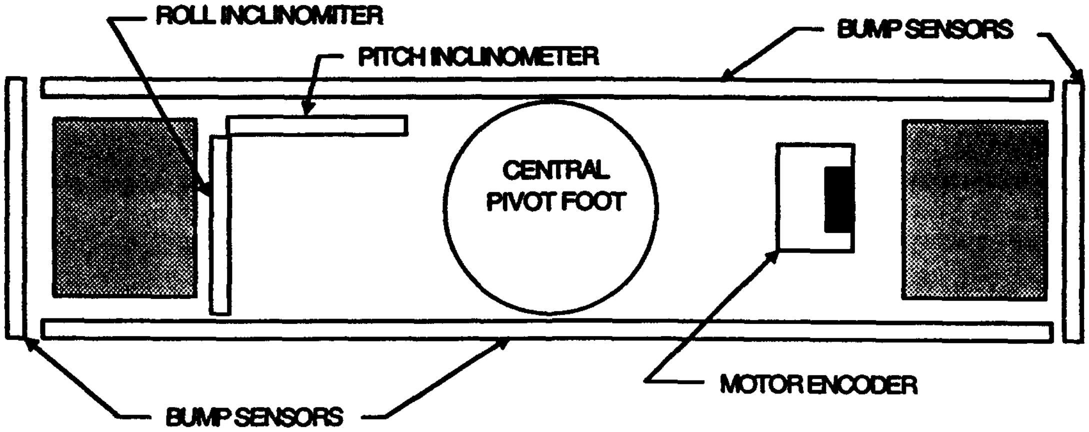


Figure 1 Robot Sensor Layout

1. The robot is placed into the bottom of the tank. When powered the robot does not know where it is within the tank.

2. To orient the robot with the central axis of the tank the robot will be run through an automated routine that will establish the orientation. The routine drives the robot forward and backward a fixed distance while watching the pitch inclinometer. The robot is stopped at the calculated bottom of the tank and rotates a specified angle. The robot is again driven forward and backward while watching the inclinometer and the robot is stopped at the calculated bottom of the tank. The data from the two runs is interpreted into a relative heading for the

central axis of the tank. This process may be repeated with averaging to improve the accuracy of the initial heading. Using the data collected the tank diameter is also calculated and compared with the historic data.

3. Once oriented, the robot is turned with the central axis of the tank and the incline of the tank is read from the pitch inclinometer.

4. The robot is driven to one of the end caps. This is detected by the bump sensor. This location becomes the tank reference for the inspection. Note that if obstacles or heavy sludge are present the robot may be driven up the circumference of the tank before orienting with the central axis and beginning the run.

5. The inspection begins and the robot is driven to the other end of the tank where the bump sensors indicate the contact with the end cap. The measured length is compared with the historical tank data and the automated inspection routine is started.

6. During the automated inspection the computer will monitor the pitch and roll inclinometers and the bump sensors to verify the dead reckoned position. Thresholds on the allowable variance of the inclinometer and bump sensor readings will be established and the inspection will be stopped if the readings are out of range. This will occur when an object is found in the tank, the tank is deformed or the robot system has had a major slip with the wall.

7. If a bump sensor contacts an object before the end cap then the size and location of the object will be located integrating a series of bumps and moves.

8. Each endcap will be inspected by driving and integrating the bump sensors to assure complete coverage of the area.

For a vertical cylindrical tank the floor, roof and walls will be handled with dead reckoning and bump sensing.

In order to support this operating scenario the sensors must meet the following characteristics:

- Encoder for the drive and turning motions. This encoder will be an incremental encoder with resolution through the gearing of the drive train of 0.01 inches (0.25 mm).

- Inclinometers for the pitch and roll axis indications must resolve angles with respect to gravity within 2°.

- Bump sensors need to make a circuit on contact.

Tank deformations can also be measured using this configuration by driving the circumference of the tank and integrating the dead reckoning information with the pitch inclinometer.

CHAPTER 5. HAZARDOUS CERTIFICATION

The 1993 National Fire Protection Agency (NFPA), National Electric Code (NEC) Chapter 5 Special Occupancies defines gasoline and fuels as Class 1 Group D hazardous products. Class 1 hazardous locations are those areas where gasses or vapors may accumulate in sufficient quantities to produce an explosive or ignitable mixture. These Class 1 locations are broken into two divisions. Division 1 locations are areas where ignitable concentrations of vapors occur under normal conditions, such as in an UST. Division 2 locations are where ignitable vapors are usually contained in a closed system and the vapors can only escape in the event of an accident, for instance near the filler tube or vent of an UST. Both division 1 and 2 locations exist in and around the fuel storage areas where we will be operating the robotic system.

The current inspection procedures for an UST require the declassification of the hazardous environment by removing the hazardous product from the tank, purging the vapors from the tank and actively monitoring the space for the hazardous vapor concentrations. Once safe, men in environmental suits with breathing apparatus can enter and clean, inspect and upgrade the tank. Using this same declassification procedure for the tank any robot capable of completing the inspection tasks could be deployed without extra precautions.

The cost of emptying each Army tank far exceeds the cost of designing and certifying a robot. The basic premise of this project has been to enter the UST without removing the product; therefore, the design is subject to the guidelines set forth in the NEC. Sound engineering, manufacturing and operating procedures are not sufficient assurances for inspectors, owners, operators and insurers. Hazardous usage certification is the key to acceptance for operating in these environments. Underwriter Laboratories and Factory Mutual Research are the two recognized approval service companies capable of certification in the United States.

There are three ways electrical equipment is classified to operate in a hazardous environment; explosion-proof, intrinsically safe and purged and pressurized. Explosion-proof devices are designed to contain, cool, and vent any internal explosion preventing igniting the surrounding vapors. Intrinsically safe systems do not have enough energy to ignite the vapors. Purged and pressurized systems declassify the hazardous environment within the confines of an enclosure by purging the enclosure, pressurizing the enclosure and interlocking an electrical shutdown with the purged gas pressure.

The certification agencies will also be looking for static electricity control measures for all moving parts and grounding measures for the entire system as regulated by the NFPA 77 regulations governing static electricity.

To build and deploy the proposed robotic system the robot, sensors and UT system will be engineered for certification while the remainder of the equipment will be set up in a non-hazardous location. The following list summarizes our strategy for certification:

- The tether management, lighting or any other device located at the tank access will be explosion-proof or intrinsically safe by design.
- The motors, encoders, gears, inclinometers, UT sensing head, tether and camera will be enclosed in a custom enclosure that meets the criteria for purging and pressurization. The enclosure must incorporate mechanical seals to maintain the pressurization around the rotating shafts which drive the robot.
- The bump sensing for the robot will be built with intrinsically safe circuitry.
- The entire robot system will be grounded to the tank to eliminate static potential in the product.

- The couplant delivery system and the tank cleaning systems will need to address static charge issues.

The certification process is similar between the UL and FMC companies and operates as follows:

- As the client we submit a letter requesting certification of our completed product design along with the design documents.

- We will pay the certifying company to review our documentation and issue us a service agreement and cost proposal for the certification.

- Upon acceptance we deliver the hardware for evaluation.

- The certifying company evaluates the accuracy of the hardware with the product design. If there are discrepancies, the evaluation stops until the situation is rectified.

- The certifying company begins the testing program and stops work and advises the client if there are any problems. Corrective action must take place before proceeding. This process continues until the testing is satisfactorily completed.

- The certifying company then visits the client's facility and subcontractor's facilities to review the quality control procedures, inspection procedures and quality assurance documents. These items are subject to audit throughout the manufacturing life of the systems.

- The certifying company reviews all of the reports and when satisfied that all the criteria has been met ,issues the certification and lists the product.

Any difficulty encountered in the approval process or oversights in the original design will result in delays and costs. In order to avoid these costly delays we recommend the following plan:

- Early in the Phase 2 design, meet with both certification companies for a free evaluation of the concept and an evaluation of their services and procedures.

- Make a decision on which company to engage in the certification process.

- As the design of the system progresses and before design submittal for certification, pay the certification company for consultation time at approximately $120/hr to evaluate the readiness for submittal and offer expertise on the design.

- Plan on some delays in the approval process and budget time and money for rework.

Until the detailed design is complete and submitted, actual costs cannot be calculated. It was mentioned to us that a system of this complexity might take 6 months and $50,000 to obtain certification.

CHAPTER 6 SYSTEM DESIGN

RedZone has designed an automated in-situ inspection system that satisfies the requirements outlined previously. The system consists of three primary subsystems:

- the in-tank mobile robot;
- the operator console;
- the deployment and tether management system

These are represented schematically in Figure 2 System Block Diagram and graphically in Figure 3 System Overview. The following sections describe these subsystems in detail.

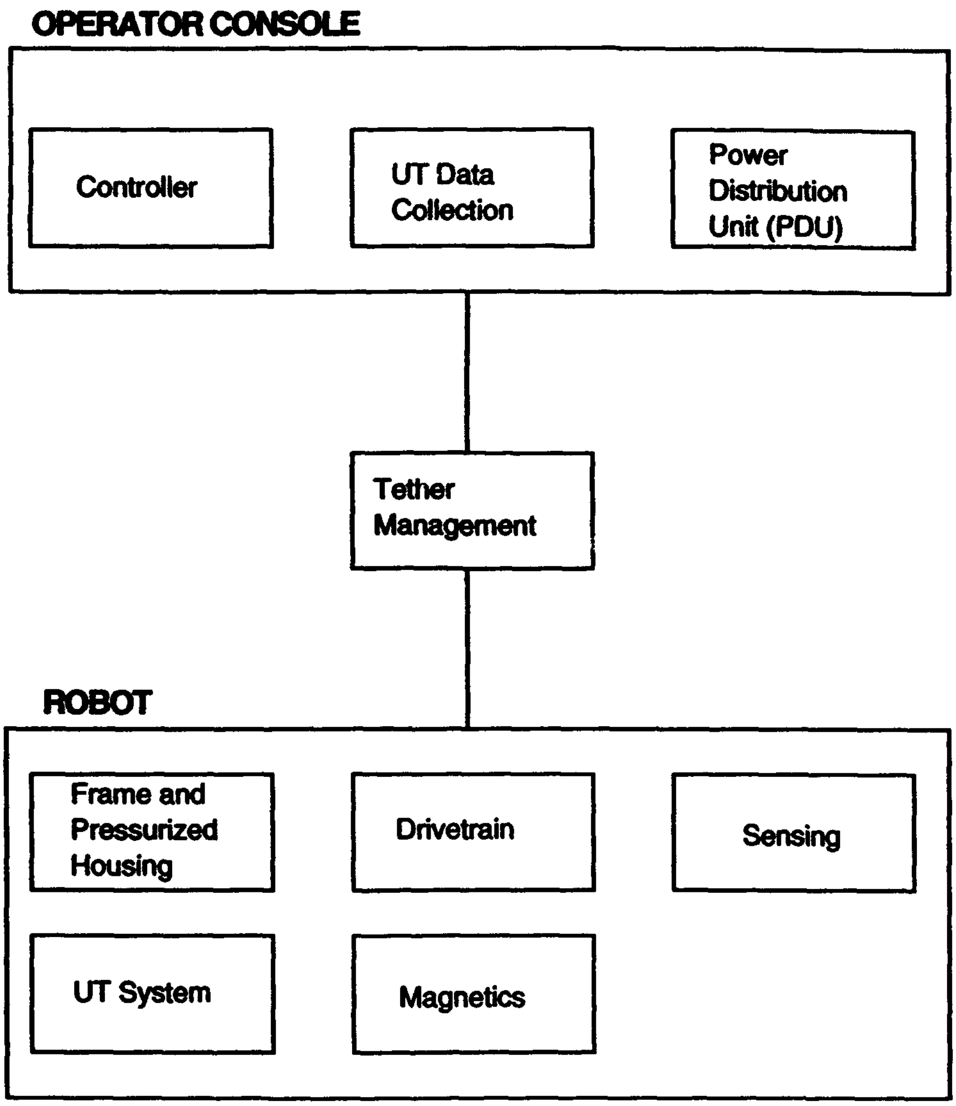


Figure 2 System Block Diagram

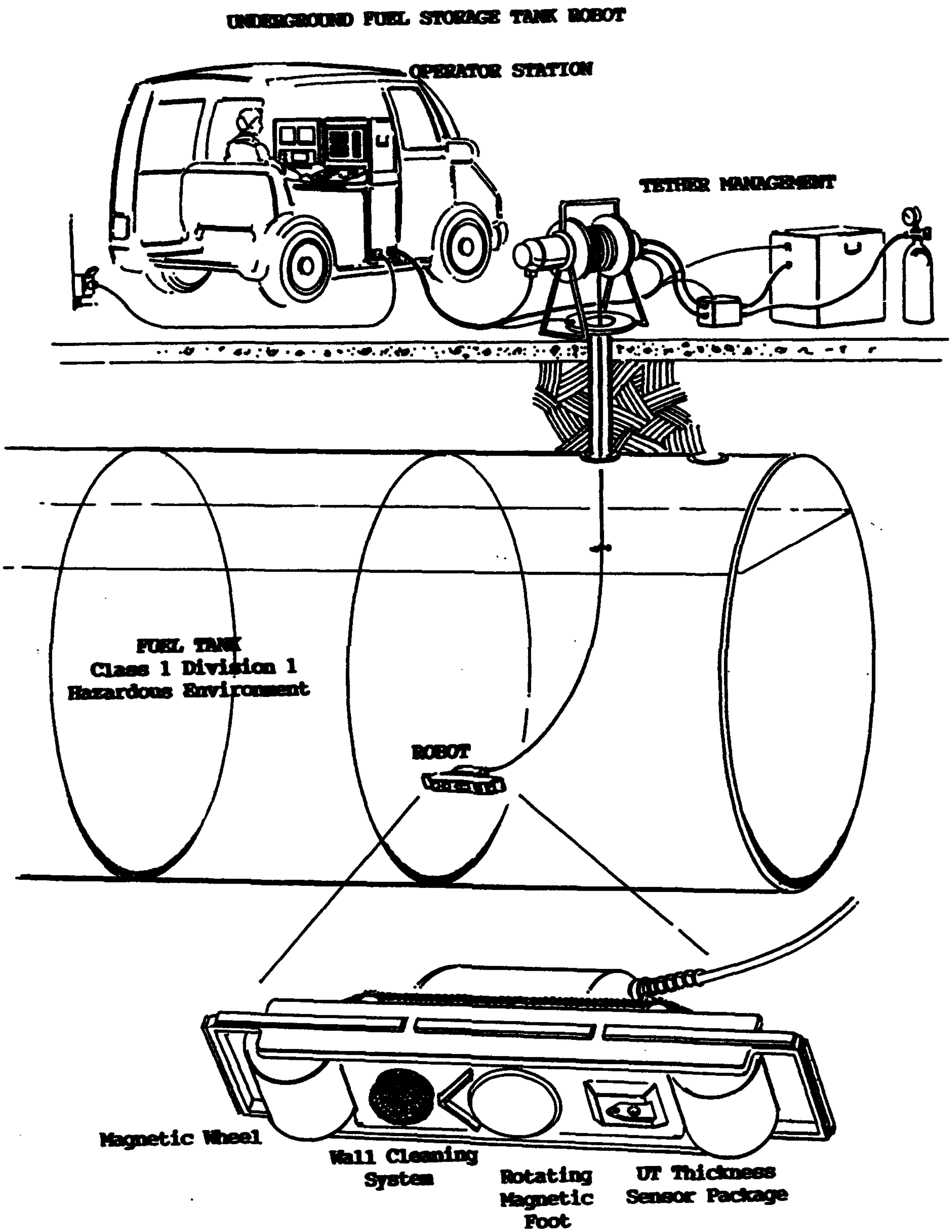


Figure 3 **System Overview**

In-Tank Mobile Robot

The robot consists of a frame and pressurized housing, drive train, sensors, magnetic and the UT inspection system. We have selected a magnetic-wheeled vehicle with a magnetic center pivot foot as the basic robot configuration. The robot will dead-reckon using a drive motor encoder.

Frame and Pressurized Housing

The robot frame will be constructed from welded aluminum plates. All of the mechanical components will be mounted to this frame. The pressurized housing will be a two-part aluminum enclosure that can be sealed, purged and pressurized. The motors, UT head, pressurized housing and the tether will become an integrated component. The motors will be mounted in the housing and the shafts of the motors pass through shaft seals rated for the hazardous environment.

The tether is sealed to the housing, allowing the gas to purge and pressurize the system. The UT sensor head is connected to the pressurized housing with tubing and becomes a part of the purged and pressurized system. The wiring for the intrinsically safe equipment will pass through a seal in the pressurized housing to the intrinsically safe components. The design of these elements is critical to obtaining certification for the hazardous environment. By layout of the key components we have determined that the mechanical system with the enclosure will pass through the 4 in. (101.6 mm) riser.

Drive Train

The drive system for the robot is powered by two motors: the servo drive motor and a foot raise/lower motor. The drive motor is a DC powered optically encoded servo motor rated for a continuous output of 1/20 hp. This motor drives a dual output through a right angle gearhead.

One side of the drive output drives the magnetic wheels through chain and sprockets and the other side of the drive output drives the rotation on the magnetic foot through a worm and wheel gear set. Because of the common drive, the wheels turn in the air while the robot spins and the magnetic foot rotates in the air while the robot drives. By using one motor to handle both motions we economize on space and lower the wire count in the robot tether.

The incremental motion between standing on the central pivot foot and standing on the wheels is actuated by a DC motor. The DC motor is powered by a power supply at the PDU, started by the computer and stopped by limit switches at the mechanical ends of the raise/lower motion. The front and rear axles for the magnetic wheels are mounted on flexible pieces of the frame allowing limited movement and compliance with the tank. This drive train design is simple, compact and will be extremely reliable.

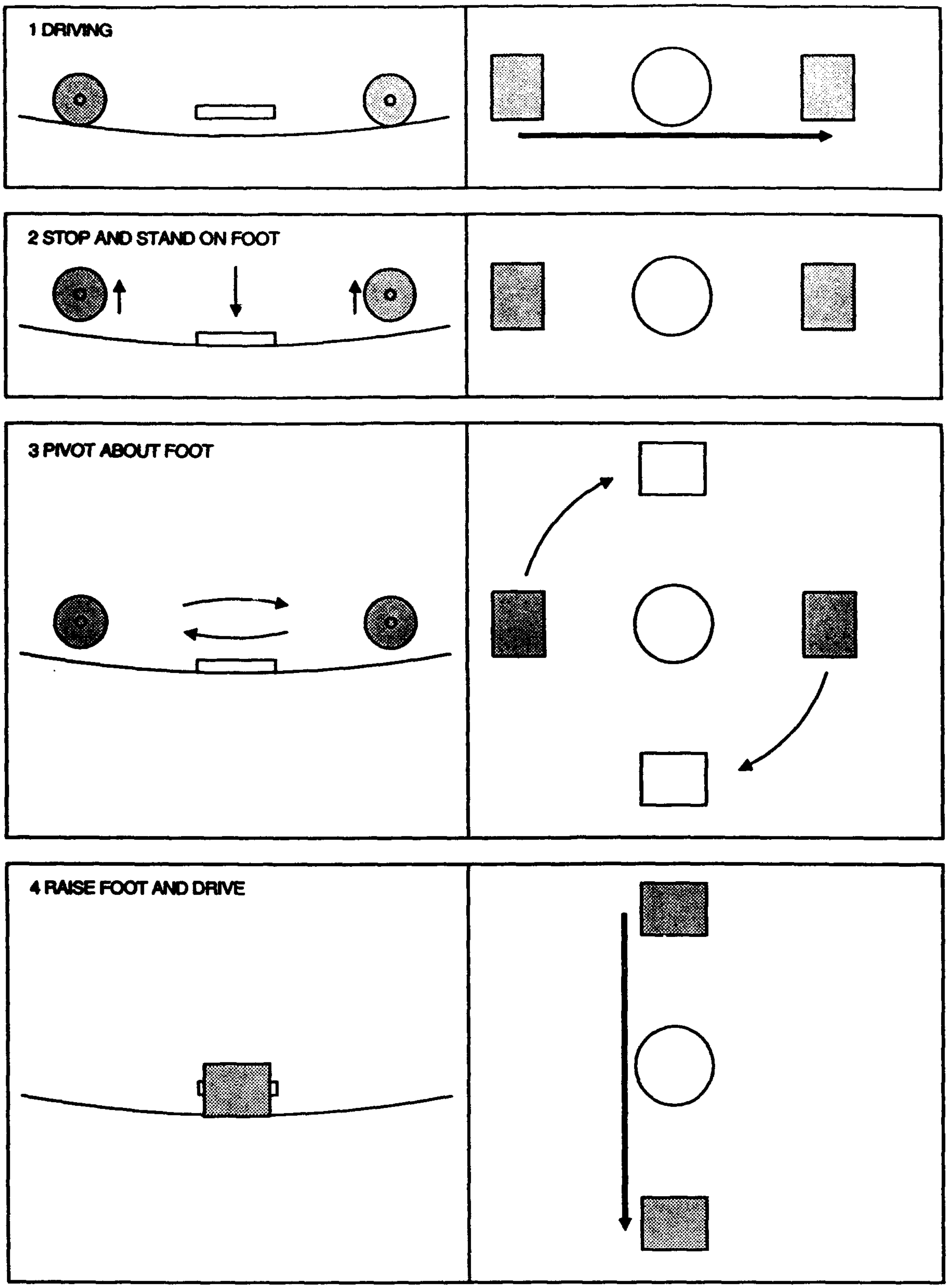


Figure 4 **Drive Motion Sequence.**

The robot will drive and maneuver through the following motions as shown in Figure 4 Drive Motion Sequence.

1. Driving - In this mode the magnetic wheels move the robot forward or backward and the relative distance is measured with the drive motor encoder.

2. Stop and Stand on Foot - To make a turn the robot must come to a complete stop and stand on the central foot. The foot is actuated by a separate motor with limited travel between "foot up" and "foot down" positions.

3. Pivot About Foot - Once standing on the foot, the drive motor drives the robot about the foot in either direction and relative angular change is measured by the drive motor encoder.

4. Raise Foot and Drive - Once the angular position is achieved the foot is raised to the "foot up" position and the driving may continue as described in step 1.

Magnetics

Because the inspection vehicle must reach all the sections of the tank interior, it must be equipped with a mechanism to hold onto the wall in any orientation. The most difficult situation is when the vehicle is on a vertical wall where the attractive force to the wall must generate enough frictional force to counter the gravity. Because the coefficient of friction is often only a fraction of unity, the attractive force must far exceed the gravitational force on the vehicle.

During Phase I, we investigated various approaches to generate such an attractive force. We have found that use of permanent magnetic force is the most promising. Because virtually all the tanks of interest are made of magnetic steel, the magnetic method is widely applicable. No controls or energy input is necessary if one makes use of permanent magnets. With today's advanced high energy permanent magnets, the system can be built quite compactly. One estimate is that the pulling force of the best permanent magnets can be as high as 10 pounds per square centimeter, about five times that of a suction cup.

While the use of magnetic force is quite attractive, we also found that rather intensive research is needed to realize its full potential. Because magnets always have two poles, one cannot simply make a wheel out of permanent magnet material. We must properly arrange the poles of the magnets so that the wheel generates adequate and smooth attractive force. Additional consideration must go to the mechanical properties of magnet materials. Permanent magnet materials are generally hard and brittle and the wheel must be designed to keep this relatively fragile component well-protected.

We have examined two basic configurations. In the first design the magnets are arranged radially at the circumference of the wheel to form multiple poles on the surface of the wheel that makes contact with the steel plate. One drawback is that the attractive force to the steel wall varies as it rotates. These uneven attractive forces will result in a torque on the wheel.

The second configuration should be free from this problem because the wheel can be constructed symmetrically around the axis of rotation. Furthermore the entire load on the wheel can be supported by the steel component alone. The design is also conducive to easy assembly. However, it requires a large amount of expensive magnet material.

The investigation to establish the relative merits of both approaches is well under way. An actual model is being constructed based on the first design because it is expected to exert the maximum attractive force. To minimize the effect of uneven attractive force, the wheels being constructed are divided into three sections. This will smooth the variation of the attractive force and minimize the torque on the wheel.

The magnetic wheel under construction is by no means optimized; there are many possible variants for the two basic designs. While under-designing the attractive force is clearly unacceptable, over-

designing can also lead to catastrophic failure because it could overload the drive motor. The magnetic attractive force varies as a gap between the magnet and the steel plate varies and the analysis of the attractive force is not straightforward.

During initial months of Phase II efforts, we will perform careful evaluation of the situation both theoretically and experimentally. The attractive force of the magnetic wheel of a given design will be calculated initially by a lumped circuit analysis to explore design principles. Once the basic design approach is established, the calculation will be refined using a finite element method. Experimental confirmation is still essential because the attractive force of the magnetic wheel depends on the condition of the steel surface. A rough and dirty surface tends to reduce the magnetic force. We will conduct a thorough investigation under realistic conditions.

UT Inspection Sensor

To take UT readings on the tank wall, the wall must be clean and the UT transducer with couplant is positioned against the wall for the reading. To accomplish the cleaning task a brush, driven by a DC motor cleans the wall surface ahead of the UT transducer. The UT transducer is imbedded in a protective carrier sled that holds the transducer square with the surface of the wall. In the sled ahead of the transducer is a couplant port which delivers couplant between the wall and the transducer. The couplant is sourced from the surface through the robot tether to the sled. In order to guarantee that the sled is in the proper position contact sensors integrated with springs indicate to the controller that the sled is normal to the wall surface and being held with a known force.

Operators Console

The operator console consists of the controller, the UT data collection system and the power distribution unit. All elements of the console will be packaged to be weather resistant, portable by one person and operate from a 110 VAC, 60 Hz single phase power source.

Controller

The controller will be based on RedZone's Intelligent Controller for Enhanced Telerobotics (ICET), a flexible, open robot controller targeted specifically at robotic applications for hazardous environments. The Intelligent Controller's modular structure allows it to be readily applied to many different robots and user interfaces. For example, as part of an RTDP Integrated Demonstration, Sandia National Laboratories developed a graphical front end to the Remote Tank Inspection System that was linked to the Intelligent Controller. The controller includes the hardware and software necessary to operate the system. The controller hardware consists of an industrial personal computer, an operator interface panel, power distribution unit and weather tight enclosure.

The computer is a commercially available industrial grade computer with the following features:

- Touch screen
- Monochrome flat screen display
- Intel 486 - 33 MHz - DX Processor
- 210 Mb Hard drive
- 12 Mb of memory
- Weatherproof keyboard

The computer will hold the following boards:

- Motion Control board - this commercial board handles the servo control of the drive motor on the robot and the reel motor on the tether management system. The motion control board has enough output bits to control the couplant supply, cleaning brush, amplifier enable signals and power up circuitry.

- Analog board - this board handles and monitors the bump switches, UT inspection head deployment contact switches, purge gas supply pressure and couplant temperature.

To interface with the controller the operator will input control functions through the touch screen and the operator interface. The touch screen will be menu driven and offer the operator several options with respect to the inspection task. The operator interface is a control panel with switches and a joystick. The operator interface will interact with the controller like the touch screen to allow the operator to acknowledge certain events. The interface will also have the overall system kill switch which will power down the robot tether.
Software modules in the UST robot controller will include:

- A Task Executive serves as the front end for the controller. It is responsible for the entire user interface, which may be as simple as a switch box with lights, or as complex as a three dimensional graphics display. Task Executive shells are available to simplify the development of new applications.

- A Health Monitor serves as a watchdog for the entire system. If key processes fail, it will either attempt to restart them, or shutdown the entire system.

- A Data Manager is the central repository for key data. Data such as the robot position are stored through the Data Manager.

- Motion Planners to plot trajectories for the robot. Typical motion planner for this robot includes end cap inspection routine, robot orientation routine, cylindrical wall inspection routines and object location and avoidance

- Motion Controllers to perform all of the low level servo control functions. Typical interfaces to these motion control boards are in the form of position and velocity commands.

UT Data Collection System

We will work with an inspection company to identify the appropriate commercial UT data collection system to integrate with the UT sensor. The commercial system must incorporate four elements: UT inspector interface, data acquisition, data recording and data reporting.

- UT inspector interface will allow the inspector to monitor the inspection while in progress and allow the calibration of the sensor before operation. Most of the commercial systems offer a menu of displays for calibration and viewing formats.

- Data Acquisition will trigger the sensing head and receive the position data from the controller.

- Data Recording will store all of the information gathered from the site in a reproducible format.

- Data Reporting will include the historic data on the UST, the inspection process data and the recorded data in an integrated report that can be transferred electronically to CERL for their evaluation. The long range commercial development system will include the data analysis and tank condition report.

Power Distribution Unit (PDU)

The PDU contains the components to power the system. The components include the power supplies, motor amplifiers, isolation circuitry, input and output solid state circuitry, the cable connector interfaces, the safety circuitry and the power wiring.

- Motor Amplifiers will be commercial DC servo amplifiers that are compatible with the motors.
- Isolation Circuitry is required for the intrinsically safe circuits. These units are sold as an integral part of an intrinsically safe sensor.
- Input and Output modules will be the modular style which plug into a commercial interface board.
- Safety Circuitry will consist of relays to interlock and prevent the unintentional powering of the system.

Deployment and Tether Management

The tether management system includes the console tether, robot tether, tether reel, couplant supply and the purge gas supply. In Figure 3 System Overview the system is shown installed in a van with the couplant and purge gas supplies shown adjacent to the riser for clarity and to reflect the stand alone nature of these components. In a van based deployment we feel that the operator will have these elements in the van as reflected in Figure 5 Van Based Deployment.

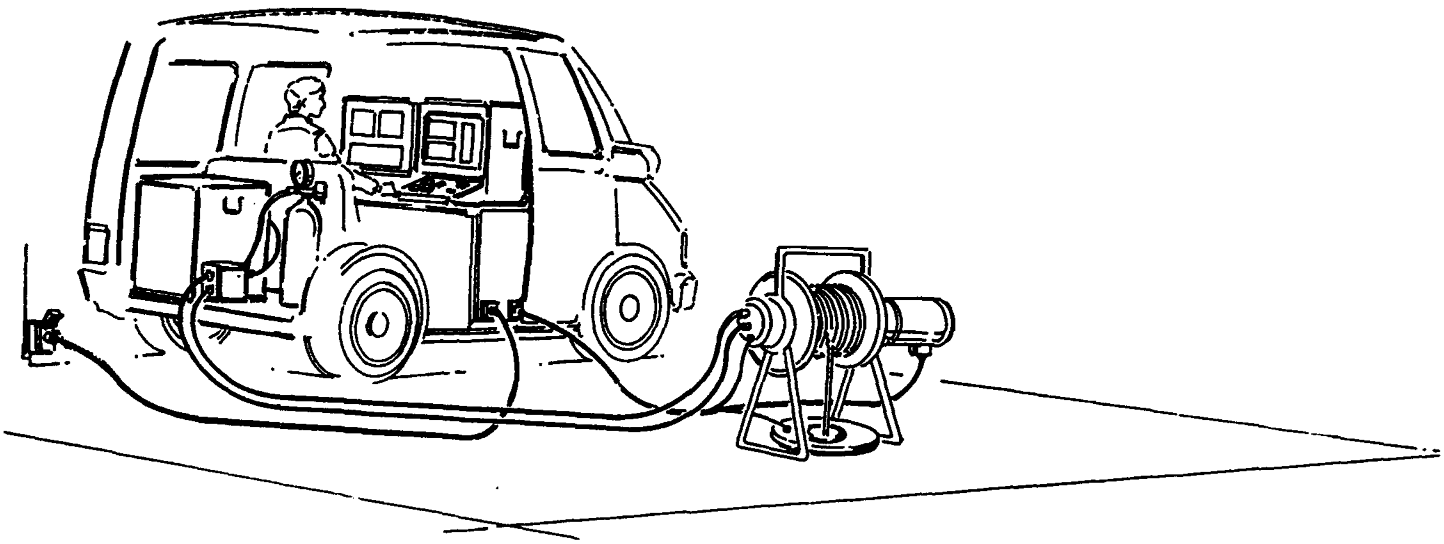


Figure 5 Van Based Deployment.

The robot tether is the lifeline of the robot and contains the couplant and wiring needed to run the inspection. The robot tether is managed by draping enough slack between the tank riser and the robot to guarantee that the robot does not run over the tether or the tether pulls to hard and dislodges the robot. This slack is managed with the tether reel at the riser and control is handled by software and the hardware at the console. The tether reel is outfitted with a slip ring to allow the reel to spin without tangling the tether. The slip ring carries the wiring, couplant and purge gas for the robot tether. The couplant supply, purge gas supply, console tether and the system ground connection are the remaining elements connected to the tether reel. The tether management integrates the robot and operators station to complete the inspection system. The following lists represent the details of the tether management system.

Console Tether

- System ground wire attaching the system to the UST.
- Couplant supply wiring to power and control the couplant supply.
- Purge gas supply monitoring wiring.
- Tether reel motor wiring.
- Electrical wiring within the robot tether.

Tether Reel

- Tether reel will be a custom reel and slip ring assembly.
- Slip ring will carry all of the tether conductors, the couplant and the purged gas line.
- Tether reel will be driven by a DC servo motor.
- The tether is actively servo-controlled during the robot operation.

Robot Tether

- System ground wire.
- 1 pair of wires for the drive motor.
- 3 pairs of wires for the drive motor encoder.
- 1 pair of wires for the cleaning motor.
- 1 pair of wires for the robot central pivot foot raise motor.
- 1 pair of wires for the bump sensors and the UT deployment contact sensors.
- 1 coaxial line for the UT sensor.
- UT couplant supply line.
- Strength member, fuel resistant, wear resistant, tubing capable of dragging the robot out of the tank, containing the pressurized purge gas and accommodating all of the tether elements.
- Purge gas.

Couplant Supply

- Reservoir for the couplant required for an inspection.
- Couplant pump to supply the couplant.
- Couplant metering to regulate flow to the tether and robot.
- Couplant heater for maintaining the temperature of the couplant in cold weather.

Purge Gas Supply

- Nitrogen Gas.
- Tank with regulators.
- Pressure transducer to allow monitoring of the supply.
- Pressure gauges.

CHAPTER 7. MOCKUP AND TESTING

We mocked-up the most fundamental aspects of the design. They include the wall attachment mechanism and the straight line drive mechanism. In this task we determined the components which require mock-up to verify performance and noted limitations from the original specifications and detailed our findings.

Mockup Components

The test setup contains the following elements:

- Underground storage tank mockup.
- Personal computer with a motion control card.
- Software supplied with the motion control card.
- Motor amplifier and power supplies.
- Mockup robot.

UST Mockup

In order to test UST robot mechanisms we installed a portion of an used UST in our facility refer to Figure 6 Underground Storage Tank Mockup. The mockup has the following characteristics:

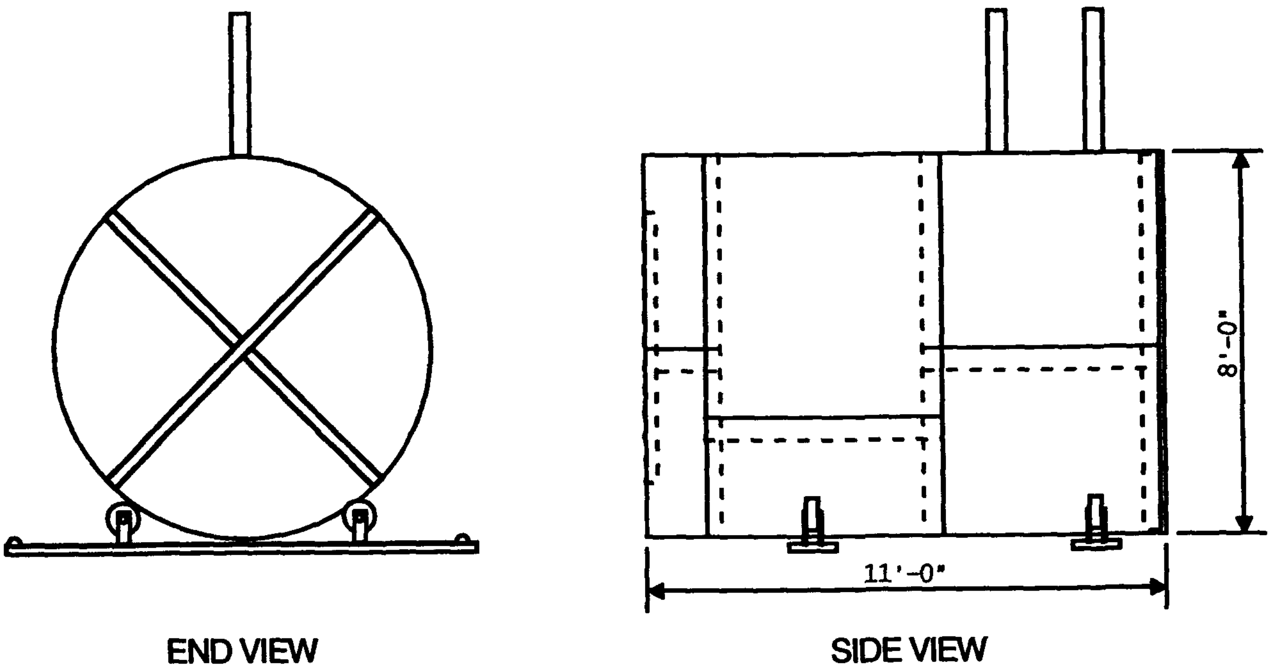


Figure 6 Underground Storage Tank Mockup.

- 15 year old gasoline tank, recently excavated and cleaned

- Minimal amounts of sludge

- No visible pitting

- Rust and scale on the interior is minimal.

- Tank is 8 ft (2.4 m) in diameter.

- Tank is cut to 11 ft (3.4 m) from the original tank.

- One end of the tank was left with the original rolled flange cap and the other end is open and cross braced with steel angles.

- Tank is constructed of 1/4 in (6.4 mm) thick steel plates that are welded in overlapping bands.

- 2 in (50.8 mm) by 2 in (50.8 mm) by 1/4 in (6.4 mm) thick steel fabrication tabs remain in the tank. These tabs were used to align the plates during the original fabrication process and now represent random obstacles to the inspection.

- Two 4 in. (101.6 mm) access riser openings exist.

- One 3 ft (0.9 m) 4 in Schedule 40 access pipe installed in one riser

- A rolling floor support to hold the tank allowing rotation of the tank and deployment of the robot from ground level

The mockup can be easily upgraded to include the addition of calibrated corrosion plates, interior obstacles and an end cap to allow filling of the tank with fluid. The mockup will not be filled with fuel. This tank mockup will serve phase 2 robotic development and testing.

Mockup Electronics and Software

The personal computer, motion control card, motor amplifier, power supplies, wiring and a 30 ft (9.1m) tether were integrated in a bench top setup to conduct the testing in the mockup. Software supplied with the motion control board allows low level commands to and feedback from the drive motor on the mockup robot.

Robot Mockup

The mockup robot consists of the following, derived from the mechanical design described in Chapter 5 of this paper:

- 2 cylindrical magnetic wheels 2 .125 in (54.0 mm) in diameter and 2-3/16 in (55.6 mm) long were custom built. The custom magnetic wheels purchased provided extremely good attraction to the tank walls.

- The drive motor is a DC brushed motor with an integral 500 line encoder and 500:1 gearhead. This motor and gearhead provided the desired torque but not the desired velocity. This limitation was a decision based on short term availability of components.

- Other drive components consist of a right angle gearbox, sprockets and chain. The right angle gearbox, chosen due to availability, broke early in the testing. The gearbox failure occurred when the helical gear pressed onto the shaft in the gearbox was overtorqued.

Attempts to rebuild the gearbox failed. This right angle gear drive is the configuration that we desire for the final version.

- To continue the testing the robot drive train was re-configured with the motor parallel to the wheel axles. The motor was coupled to one magnetic wheel with the use of chain and sprockets. The chain sprockets were subject to slipping on the shafts even when glued and set screwed in place. These mechanical components must be ruggedized in the phase 2 designs.
- The mounting frame is constructed from 2 side plates and various brackets that integrate all of the components.
- The mounting frame places the 2 magnetic wheels 16 in (0.3 m) apart axle to axle.
- The foot rotation could not be integrated into the mockup in the time and budget remaining in this project.
- The robot weighed 10 lbs in testing.

Using this set up we conducted the following tests:

- Mobility tests
- Positional dead reckoning accuracy test.

Mobility tests

Mobility test objectives

- Fit through a 4 in (101.6 mm) schedule 40 pipe.
- Driving effectively in the mockup.
- Driving over the plate transitions.
- Evaluating what is needed to make safe wall transitions.

Mobility test procedures

Mobility test procedures took place in the tank mockup:

1. Fit the robot down a 4 in (101.6 mm) schedule 40 pipe.
2. Drive straight along the bottom of the tank and return.
3. Drive the inside circumference of the tank.
4. Drive randomly around the tank.
5. Drive square into the endcap and try to make the transition onto the cap. If the robot does not successfully transition, determine what is needed to make the transition consistently.

Mobility test Conclusions

Mobility test observations:

1. The right angle drive train configured robot fit through the 4 in (101.6 mm) schedule 40 pipe. The length of the motor when turned parallel to the magnetic wheel axle would not fit through the pipe.

2. The right angle drive robot functioned on the bench top; but failed in the tank mockup due to overtorquing.

3. The robot drove in repeatable straight line paths in forward and backward motion in any orientation in the tank. The robot could climb over the 1/4 in (6.4 mm) plate seams without any problem.

4. The robot motion was jerky due to the magnetic effects of the wheels. With the drive train disconnected it took 10 lbs of force to overcome the magnetic pull of the wheels to begin moving. When driving, this jerky motion severely impacted the basic drive components and will require much better construction for phase 2.

5 The leading magnetic wheel stuck in the corner of the plates trying to make the transition from the tank wall to the end cap. We found that a gap as small as 1/4 in (6.4 mm) between the wheel and one of the plate surfaces allowed this transition to occur smoothly. The rear wheel also sticks as it tries to make the transition and by providing the small gap the transition continues smoothly.

Positional dead reckoning accuracy test
The final version of the mockup robot limited this research to straight line tests.

Positional test objectives:

Accuracy of a driven path.

Positional test procedures

Command and drive a straight paths and measure the actual distance traveled.

Positional test Conclusions

Table 1, Position Accuracy Tests reflect errors of less than 3% in all test runs. The accuracy of a phase 2 system integrating better components should yield much smaller positional errors.

Velocity CTS/SEC	Start Position Counts	End Position Counts	Distance Measure Inches	Distances by Enc Calc. Inches	Error
Horizontal Tests					
50000	0	-7836757	60	59.69	0.52%
50000	-7836757	-71387	60	59.21	1.32%
100000	0	-7718879	61	60.47	0.86%
100000	0	7752081	60	60.25	0.42%
150000	7752081	1535	60	60.24	0.40%
200000	0	7691522	60	60.66	1.09%
200000	7691522	-5649	61	60.69	0.50%
250000	-5469	7708896	61	60.58	0.70%
250000	0	7566417	62	61.49	0.82%
Vertical Tests					
50000	0	7812045	60	59.85	0.25%
100000	0	7905011	60	59.23	1.28%
150000	0	7938046	60	59.01	1.65%
200000	0	8009491	60	58.53	2.45%
250000	0	7796884	60	59.95	0.08%

Table 1 Positional Accuracy Tests

Design Conclusions

- We can make the end cap transitions by integrating a mechanical device to separate the magnetic wheel from 1 plate surface.
- We identified that extra torque is needed in the drive train design to overcome the magnetic pull of the wheels.
- We traversed all of the surfaces including the plate seams in the tank in any orientation with no problems.
- We can fit down the 4 in riser pipe when configured in a right angle drive orientation.
- We identified that better quality mechanical components are key to providing reliability and accuracy.
- We did not get to test the rotational actuation of the robot and feel this key element should be tested early in the phase 2 program.

CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The robotic system is designed to meet the criteria outlined in the Draft Standard For The Robotic Inspection of Underground Storage Tanks developed for the EPA which sets the standards of performance for the thickness inspection by a robot in USTs.

The in tank thickness inspection is achievable with the technologies outlined in this report.

The system design must be capable of being classified for use in the Class 1 Division 1 hazardous environment.

The simplicity of the robot system outlined in this research will result in a system that is reliable and economical. This is the key to the widespread acceptance of this product as the tool of choice when evaluating the condition of an UST. This design will allow the UT inspector to be trained as the robot operator turning the entire inspection into a one-man operation.

Recommendations

The simplicity of the robot system outlined in this research will result in a system that is reliable and economical. Economy and reliability are the keys to the widespread acceptance of this product as the tool of choice when evaluating the condition of an UST. This design will allow the UT inspector to be trained as the robot operator turning the entire inspection into a one-man operation.

The hazardous classification is the key element in the acceptance for field use of these types of robotic system and the process leading to certification should begin at the start of the design.

The robot configuration that is certified for hazardous use is a patent able device and the patent process should be started with the design.

Looking at the 1998 deadline for completing action on the Army USTs there is an immediate need for the development of this technology.